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Component Research for Future Propulsion Systems

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COMPONENT RESEARCH FOR FUTURE PROPULSION SYSTEMS

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ABSTRACT

A review of the factors affecting the helicopter market for the past, present, and future is presented. The trade-offs involving acquisition cost, mission reliability, and life-cycle cost are reviewed, including civil and military aspects.

The potential for advanced vehicle configurations with substantial improvements in energy efficiency, operating economics, and characteristics to satisfy the demands of the future market are identified. Advanced propulsion systems required to support these vehicle configurations are, in turn, discussed, as well as the component technology for the engine systems. Considerations for selection of components in areas of economics and efficiency are presented.

Introduction

There are many factors related to propulsion systems that strongly influence performance of helicopters. Reviewing each of them and their impact on the past, present, and future helicopter market is not practical in the context of this paper. Most significant, however, are the trade-offs among acquisition cost, mission reliability, and life-cycle costs. Beyond these factors, detailed assessments of potential advances become extremely complicated by end usage (military versus civil) requirements and by the escalating cost of fuel. Of course, each of these concerns finds root in the component technology needed for improved operating economics, and some of the critical issues are discussed here.

Outlook/Background

The growth in all sectors of aviation has been dramatic over the last 50 years. However, it is clear that rotary-wing aircraft have lagged this growth by as much as two decades. One reason is the increased difficulty in achieving controlled flight compared with fixed-wing aircraft, and another is the dependence on the development of different technologies, specially needed for helicopter components. Despite the lag, benefits derived from these special purpose machines have been growing at a significant rate since 1960. Figure 1 indicates the rate at which the activities have enlarged in North America. Also shown is a somewhat conservative growth projection for the next 10 years, and there is an equally active future projected for the helicopter industry world-wide. In the United States alone, the production rate for civil uses has grown from 300 units in 1965 to 800 in 1975. The 1981 figure is expected to exceed 1000 units. In most cases, the technology has been paced by military interests, particularly the United States Army. Now, the civil needs are emerging, and this segment will add strength by sharing in common solutions to most of the operational problems. As shown in Figure 2, the primary applications will be in forestry, public service, agriculture, resources exploration, and construction, in addition to short-haul, general transportation. Thus, there is a base to enlarge the research activity for both military and civil needs, and the generic aspects cover a wide spectrum of components from which substantial gains can be made. NASA's rotorcraft program evolved from autogyro research during the 1930's (at that time it was known as the National Advisory Committee for Aeronautics, NACA). From this pioneering effort, a close association later was developed with military rotorcraft R&D organizations. One of these strong ties was with the US.Army, resulting in a number of formal and informal cooperative efforts. The latest such agreement became effective in 1970. With it, NASA and the Army share resources to pursue research in areas of common interest, including all helicopter disciplines related to aeromechanics, structures, and propulsion. As a result, Army research groups, colocated with NASA, conduct inhouse and contracted efforts on all components of engines and drive trains, including materials. It is this association that is bringing into focus the commonality aspects of the civil and military interests as applied to fundamental problems and basic technology. To complement this joint effort, NASA formed a government-wide task force in 1978 to assist in formulating a long-range advanced rotorcraft technology program.

Systems Requirements

Civil operators continually emphasize a true, one-engine-inoperative (OEI) capability. They are unanimous in their endorsement of twin-engine helicopters, but they are unhappy with single-engine performance in the OEI mode. Ideally, these operators want a nonemergency situation in the event of an engine failure. As shown in Figure 3, their goal is to achieve a zero-rejected takeoff distance to enable operations in tightly confined areas, consistent with the attributes of helicopter systems.

Regardless of the user, safety and reliability continue to be the central issues. Although safety of twin-engine helicopters is regarded as an inherent advantage, unscheduled engine removals continue to frustrate all users. Dissatisfaction with support requirements and the attendant high costs are common. The component research programs must include emphasis on significant increases in the time between overhauls (TBO).

Maintenance costs associated with propulsion and drive-train systems are shown in Figure 4. A major reduction in maintenance costs is essential to the enhancement of helicopter operations. Beyond this need, recent advances in diagnostics and associated avionics are already finding their way to the market. With continuing progress in microprocessor technology, early identification of engine and drive-system problems, before they become serious, may provide the techniques for maximizing use of on-condition maintenance procedures. Figure 5 illustrates the need for significant improvements.

Electronic digital controls can provide large improvements over conventional hydromechanical systems in terms of simplicity, cost, reliability, and ease of operation. An example is shown in Figure 6. Time response characteristics of the total propulsion system (i.e., engines, control, and power transfer mechanisms) must be evaluated in a totally integrated mode. These evaluations must be conducted in systems which simulate, as closely as possible, the environment that will be encountered in service.

Powerplants and Component Thrusts

Since the advent of turbine engines for helicopters, a dramatic increase in load-carrying capability has evolved. Almost all of these turboshaft engines were developed for military helicopters, and each is based on technology derived from military-sponsored development. Even so, it is expected that the next two decades will find a growth in the civil markets to the extent that the number of engines produced will be about twice the military needs. This growth, combined with the comparatively high usage rate (2000 flight hours per year) for civil units, will substantially enhance operational evaluations of engine-related technologies. The civil demands for reliability, maintenance, and overall cost will be stronger than at any time in the past. The experience with large field samples will be invaluable.

Performance improvements have become essential, particularly for those future helicopters that will be designed for increased range and speed. Toward that end, perhaps more complex engine arrangements, using highly loaded components, recuperators, and variable geometry will be required. If so, we must be in position to compensate for the likelihood of higher initial costs with superior, fuel-efficient engine systems. Obviously the engine cycle must be improved in the partial-power regimes, shown in Figure 7, and emphasis must be placed on methodology to provide aerodynamic components that will produce a specific fuel consumption characteristic more nearly flat than in today's conventional cycles.

In an overall sense, the objectives of the NASA-Army propulsion efforts are to (1) improve engine and power transfer component reliability and maintainability, (2) reduce engine fuel consumption over the full range of operation, (3) improve environmental acceptability, and (4) reduce the cost of acquisition and operation. The highest priority program element is component design methodology, as applied to each of these areas. More specifically, achievement of the objectives will concentrate on the six key technology task categories shown in Figure 8. Each of these program elements has been reviewed by a broad spectrum of civil and military users and, despite the diversity of missions, there remains a remarkable unanimity on the areas in need of most immediate attention. Concerns relating to powerplants appeared to lead the list of priorities.

Although the current program covers all components of interest, this discussion will concentrate on those considered to have significant impact on the above thrusts.

Compressor

In a gas turbine engine, the compressor design and technology are very important choices because of the effect on the overall engine performance and arrangement. Compressor pressure ratio and compressor efficiency have a direct bearing on fuel consumption. At the same time, the compressor can have an influence on the number of turbine stages as well as the number of spools.

Because of the important role of the compressor in the overall engine, a joint Army/NASA program was undertaken with General Electric, Detroit Diesel Allison, and AiResearch for design studies of small, axial, centrifugal compressors to provide a basis for focusing future research on small compressors. These studies started with a forecast of the projected 1990 state of technology in compressors and engine systems. The projections forecast improvements in technology derived from existing work, from advances in materials processing and manufacturing methods, as well as improvements from advances in design techniques and computer aids. Based on these 1990 projections, parametric studies were conducted on compressor configurations for 2-, 5-, and 10-lb/sec flow sizes. Four staging arrangements (single staged centrifugal, staged centrifugal, staged axials, and staged axial-centrifugal) were investigated. Compressor pressure ratios from 10:1 to 40:1 were studied. The optimum compressor arrangements for 2, 5, and 10 lb/sec were identified in terms of efficiency, reliability, durability, maintainability, and cost (Fig. 9). In the 2 and 5 lb/sec flow sizes both axial centrifugal and staged centrifugals configurations have the best potential for advanced rotorcraft propulsion systems. In the 10 lb/sec flow size, the axial centrifugal compressor configuration appeared to provide the greatest potential efficiency at the high cycle pressure ratio.

Improved theoretical aerodynamic analyses, verified by detailed quantitive data, will help improve the understanding of the complex flow field for the advanced axial and centrifugal stages. Techniques for the calculation of the internal flow field in centrifugal compressor using three-dimensional viscous computational methods are being developed (Fig. 10). To date, we do not have analyses which can represent the actual flow conditions with reasonable computing times.

Recent advances in the application of laser anemometers, or laser doppler velocimeters, permit measurement of flow velocities and mapping of the flow field. In Figure 11 the covers have been removed from the compressor to show the laser beams crossing. Windows in the housing permit the beams to be directed into the rotating passages or into the diffuser area. Problems with seeding are delaying testing at higher speeds in small centrifugals, but we are hopeful of having a nonintrusive means of obtaining flow information in small passages where probes previously disturbed the flow. The laser anemometer will be an extremely valuable tool for developing an understanding of the complex flow areas such as the discharge region at the tip of the impeller. This area is most critical because it is here that the diffuser converts the high velocity into pressure.

Other improvements will involve variable flow capacity, where variable geometry is used in the compressor and turbine areas. An essential feature is the capability of a variable diffuser for the centrifugal compressor. This will permit the flow to be reduced while maintaining or increasing the pressure ratio and operating at a constant corrected speed. Consideration must be given to the mechanical design features required to implement this system in light of the gains to be achieved.

Beyond this, there will be improvements in small compressor performance with clearance control, reduced endwall and profile losses, and low aspect ratio blading, which is less sensitive to wear.

Combustor

As compressor pressure ratios are increased, future combustion systems for small turboshaft engines will be required to operate at higher pressure levels and increased inlet and exit temperatures, which will increase the need for better cooling of liner materials. Programs are ongoing at the Lewis Research Center on both approaches. One example is a plasma-sprayed ceramic on a porous metal substrate as shown in Figure 12. This approach will permit a significantly higher liner hot-side temperature and permit cooling the substrate with much less cooling air.

Both combustor and turbine life are adversely affected by nonuniform combustor exit temperature. At the same time, the need for improved fuel economy makes desirable the reduction in pressure drop across the combustor. These two goals are in conflict because temperature pattern is easier to control with larger pressure drop. Improved modeling and analytical techniques promise to reduce the cost of developing combustors, and there has been significant progress made in this area for small, reverse-flow combustors. However, such studies have indicated the need for additional research in fuel-injection methods and in primary zone analysis and experiment. One such investigation is illustrated in Figure 13.

With these two areas of research, it is expected that designers of future engines will have better materials, better cooling schemes, and improved techniques for selection of parameters to make trade-off decisions affecting combustor life and fuel efficiency. In addition, they can expect the relative development cost of combustor components to be reduced because of improved analytical tools that have been verified by experiment.

Turbine

Current research for the small turbines used in helicopter engines is directed at improved efficiency and higher temperature capability. The primary thrusts are for fuel efficiency and longer life for maintainability and life-cycle cost purposes. Materials research is primarily directed at this latter requirement with emphasis on coatings--metallic coatings for oxidation and corrosion protection and ceramic coatings for thermal protection and reduced cooling requirements.

One means of improving turbine efficiency in the small engines is to utilize a radial flow instead of an axial flow turbine. It is recognized as heavier and more bulky than its axial counterpart, but, as shown in Figure 14, it has potential for better performance at high pressure ratios. The radial turbine also is best suited to a variable capacity engine, which may offer an advantage in fuel consumption over a fixed-geometry configuration. To maintain design point pressure and speed, the nozzle area needs to be varied in some manner such as illustrated in Figure 15. Current analytical and experimental research is directed at understanding and quantifying losses due to the variable geometry to permit a realistic assessment of the fuel saving potential of such a concept. Figure 16 shows experimentally derived efficiency of a variable-area configuration over a wide range of flow at a pressure ratio of about 2:1. While these data do not include stator leakage effects and losses that might occur with high exit swirl, consideration must be given to these factors as analysis and experiment are continued. However, the reasonably constant efficiency is encouraging and shows that this concept has potential for a practical variable capacity cycle. At the very least, research along these lines will permit designers of future helicopter engines to incorporate high-work radial turbines in their engines with higher efficiencies than now possible.

As the technology advances for employing nonintrusive flow measurements, such as laser anemometry, measurements will be made to further the understanding of the flow in radial turbines. Three-dimensional analytical techniques, when verified, will provide the basis for further advances in both the efficiency and cooling of radial turbines.

Mechanical Components

Our present concern for fuel conservation and the need for better performance retention necessitate improved seals. Many engines use labyrinth seals for inner air seals. Generally, these seals employ one or more stages of knife edges and, in the higher performance engines, have shown a high leakage rate. To overcome this problem, face-contact seals sometimes have been used; however, they are pressure and speed limited and have excessive wear. Recognizing this shortcoming, a high-speed spiral-groove seal has been developed through joint Army/NASA efforts. It offers a solution and can be regarded as a step in technology for replacing both the labyrinth and face contact seals. As shown in Figure 16, this type of seal has shallow recesses in the running surface which cause a buildup of high pressures and prevent actual contact of the carbon face, except during start up. This seal has potential for application in both current and future engines.

Of all the seals in an engine, the gas-path seals have the greatest impact on performance. Tests have shown that an increase of 1 percent in blade-tip-clearance-to blade-span-ratio reduces the turbine efficiency by as much as 3 percent, depending on the type of the turbine design. The effect is shown in Figure 17. Generally, the gas-path-sealing clearances change with each engine condition such as idle, takeoff, and cruise. A joint Army/NASA program to develop a solution has been in progress for several years, exploring various ceramic high-pressure-turbine seal systems. One concept, which is currently under investigation, shows potential. It employs a low-modulus cushion or strain-isolator pad between the ceramic layer and metal substrate, depicted in Figure 18. The strain isolator pad allows the ceramic layer to respond to its own temperature gradient, independent of the thermal strains and displacements of the metal substrate. In conjunction with this system, clearance-control concepts involving selection of materials as well as rotor and outer structure configuration to maintain a fixed clearance, are under investigation. Variables also include thermal expansion rates, and the potential for using

engine air to heat and cool the mating rotor and stator. Also, blade tip treatment concepts are under investigation to prevent damage to the blade tips at contact with the case. These seals will become more practical as materials, design concepts and manufacturing methods are developed further.

In the area of shaft dynamics, there have been several Army, NASA, and industry programs to develop improved balancing techniques for rotors. In addition, a new computer code, which is capable of predicting nonlinear rotor dynamics, has been developed. This code allows investigation of transient rotor motion during adverse operating conditions, such as a blade loss with a rub. Previously, shaft behavior could not be predicted with available rotor dynamics codes. Damper concepts also are being analysed, primarily to explore rotor systems that will be more tolerant to a large imbalance, as in cases equivalent to the loss of a blade or foreign object damage.

Research on bearings will continue to focus on optimizing design through improvements in materials and lubrication for higher-load capacity and longer life. Computer programs incorporating the latest design techniques are in various stages of development and verification. Speeds over 50,000 rpm are common, and a moderate increase is forecast for the future. Along with this emphasis, there will be an increased attention placed on noncatastrophic failure of bearings operating at higher speeds.

Conclusion

In pursuing these areas of research, we have highlighted but a few of the many component details that need special treatment. All of the components technologies, whether in engines or drive trains, are supported by an aggressive program covering all facets ranging from aerothermodynamics to materials and structures. It is hoped that the growth forecasted for the helicopter will provide added incentive to concentrate the needed resources in the critical areas identified here. In cooperation with the industry, NASA and the Army will continue to explore the components and develop the technology to meet the growing needs, particularly as related to reliability and life-cycle cost.

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ROTORCRAFT GROWTH AIRCRAFT/HELIPORTS/OPERATORS

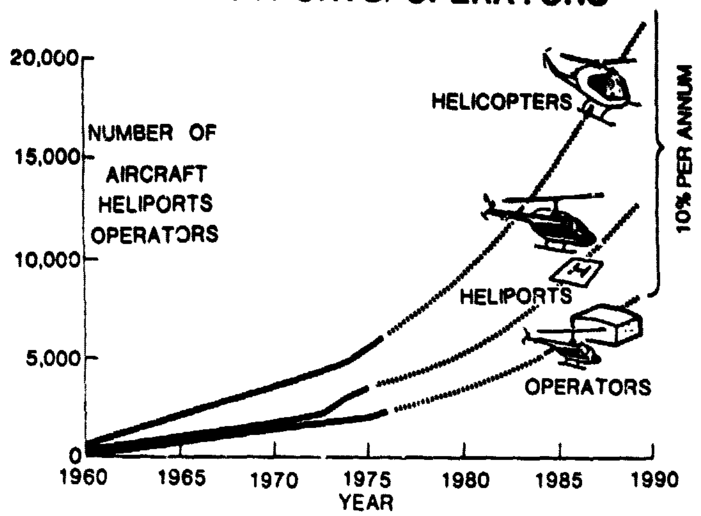
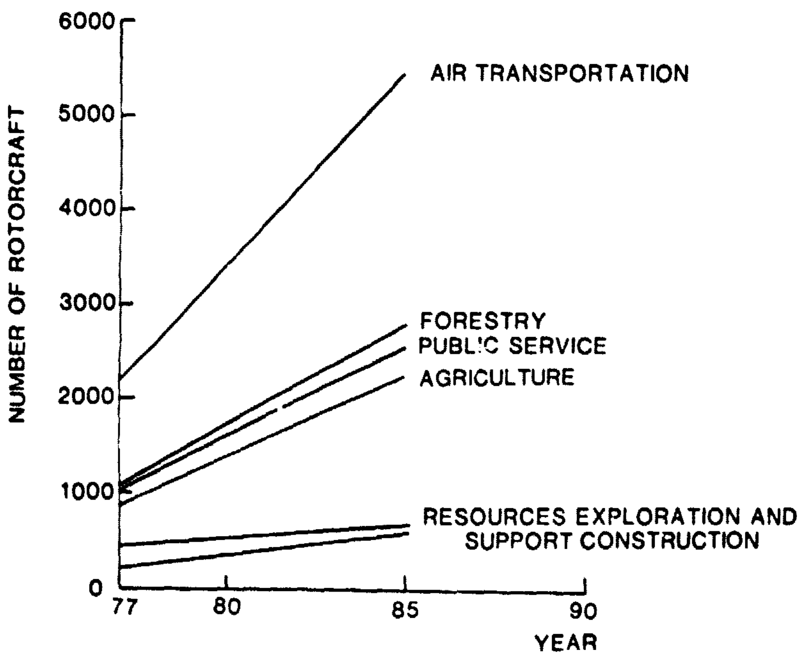


FIGURE 1

PROJECTED ROTORCRAFT GROWTH PATTERNS



SOURCE OF ACTUAL DATA : 1977 DIRECTORY OF HELICOPTER OPERATIONS
AIA WASHINGTON D.C. 1978

FIGURE 2

CATEGORY A REJECTED TAKEOFF DISTANCE

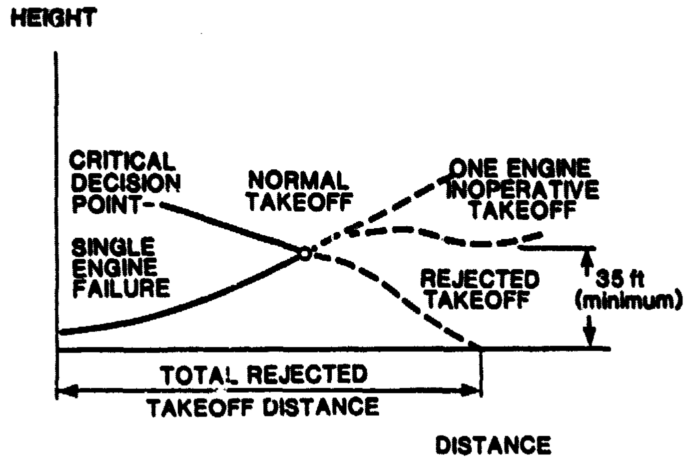
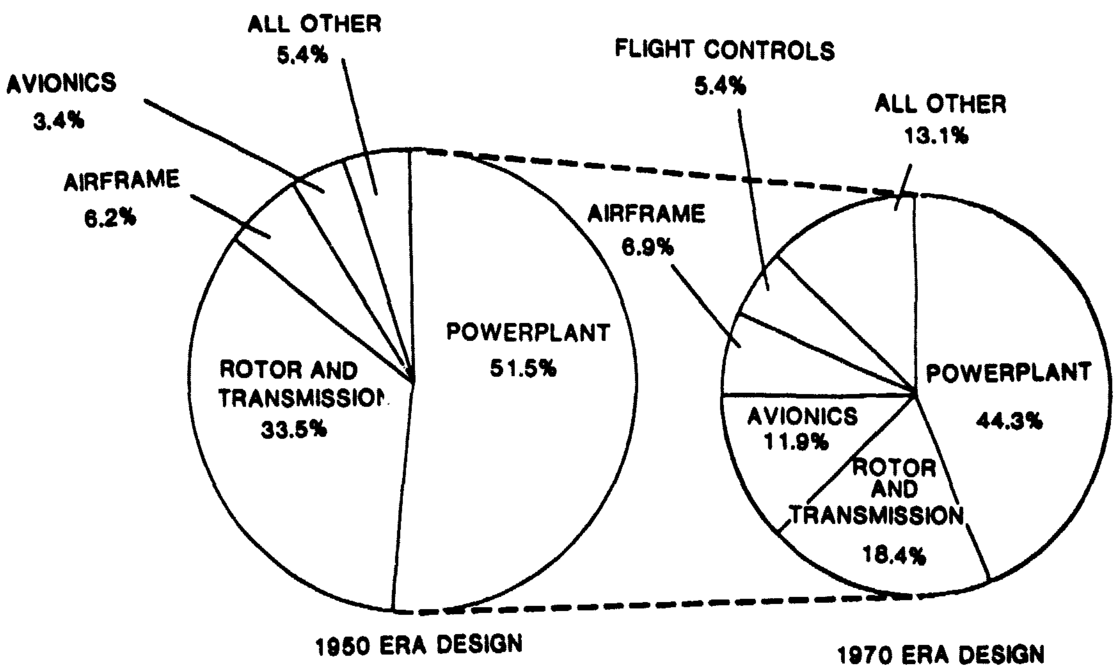


FIGURE 3

HELICOPTER MAINTENANCE COST DISTRIBUTION

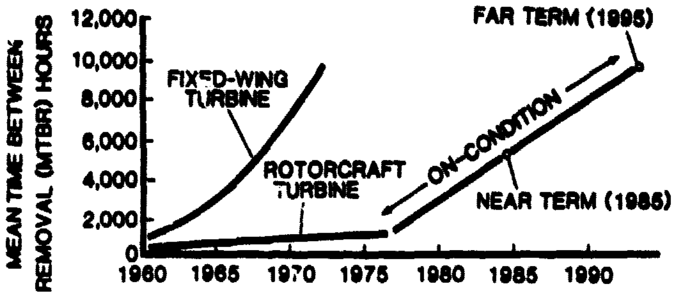


SOURCE:

1. 1950 DESIGN BASED ON ASSESSMENT OF UH-1H CONTAINED IN TR75-3
2. 1970 DESIGN BASED ON BOEING VERTOL YUH-61A DMC STUDY , DECEMBER 1975

FIGURE 4

ENGINE TECHNOLOGY GOALS



INCREASED ENGINE RELIABILITY THROUGH:

- IMPROVED ENGINE COMPONENT TECHNOLOGY
- IMPROVED CONTROLS TECHNOLOGY
- ADVANCED SYSTEMS MONITORING TECHNOLOGY

FIGURE 5

INTEGRATED ELECTRONIC DIGITAL CONTROLS

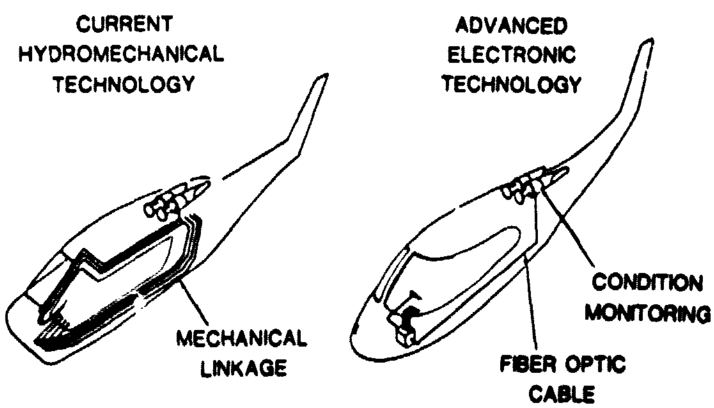


FIGURE 6

ROTORCRAFT ENGINE SPECIFIC FUEL CONSUMPTION CHARACTERISTICS

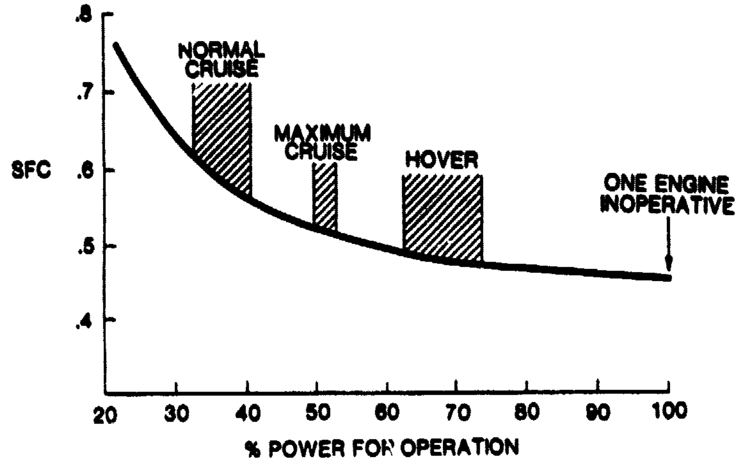


FIGURE 7

ENGINE COMPONENT DESIGN METHODOLOGY

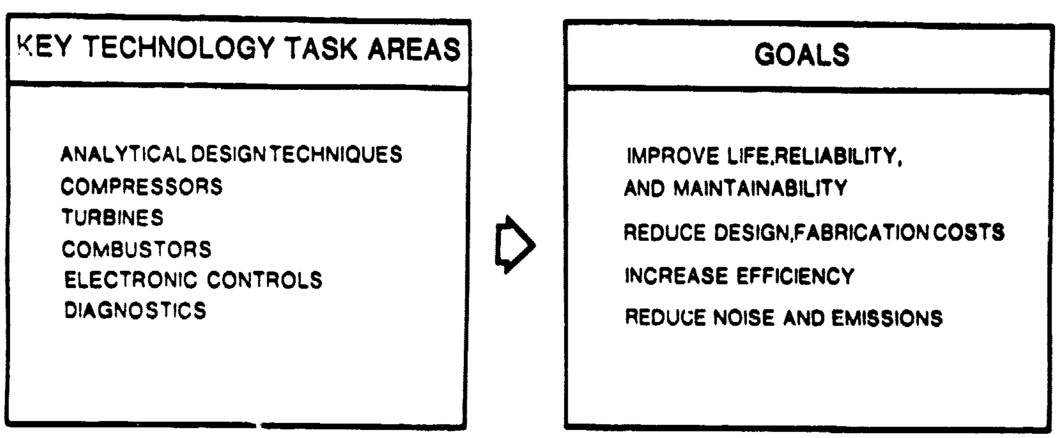


FIGURE 8

COMPRESSOR CONFIGURATIONS

ARMY-NASA-INDUSTRY JOINT EFFORT

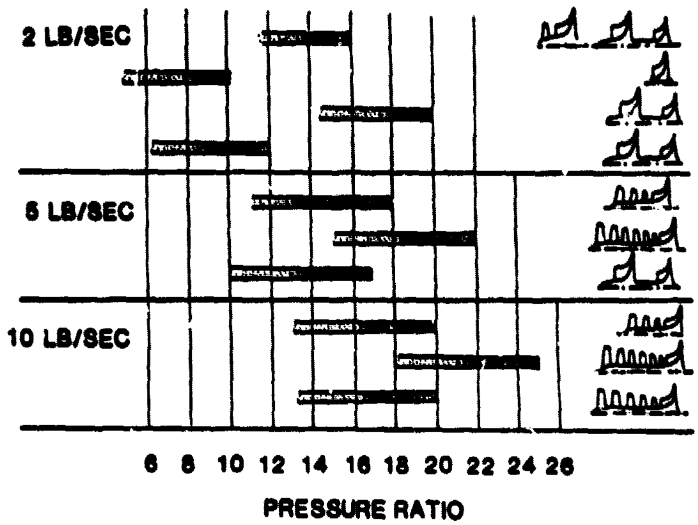
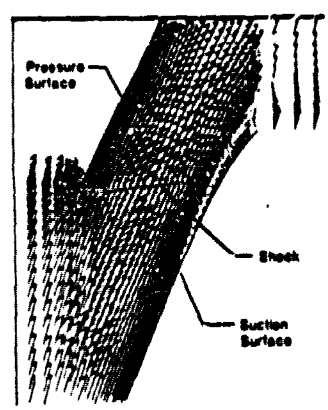


FIGURE 9

COMPUTATIONAL FLUID MECHANICS (CFM)

NUMERICAL ANALYSIS
OF
3-D VISCOUS FLOW FIELD
IN
CENTRIFUGAL COMPRESSOR



VELOCITY COMPONENTS

FIGURE 10

LASER VELOCIMETER

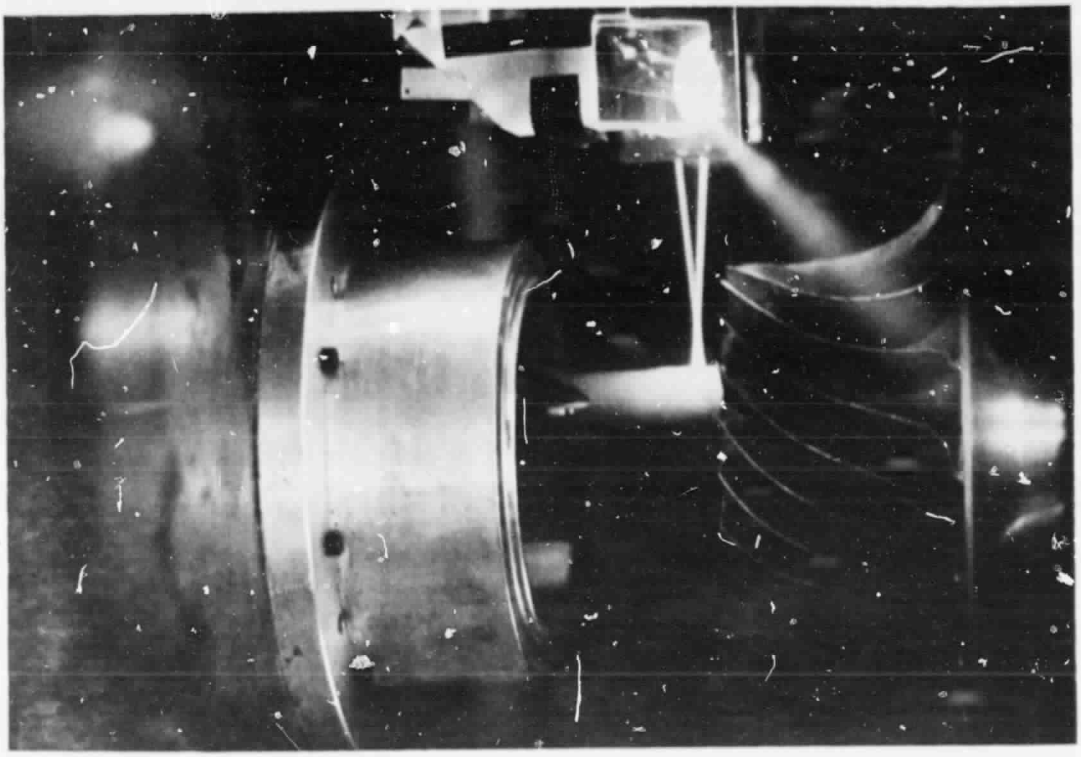


FIGURE 11

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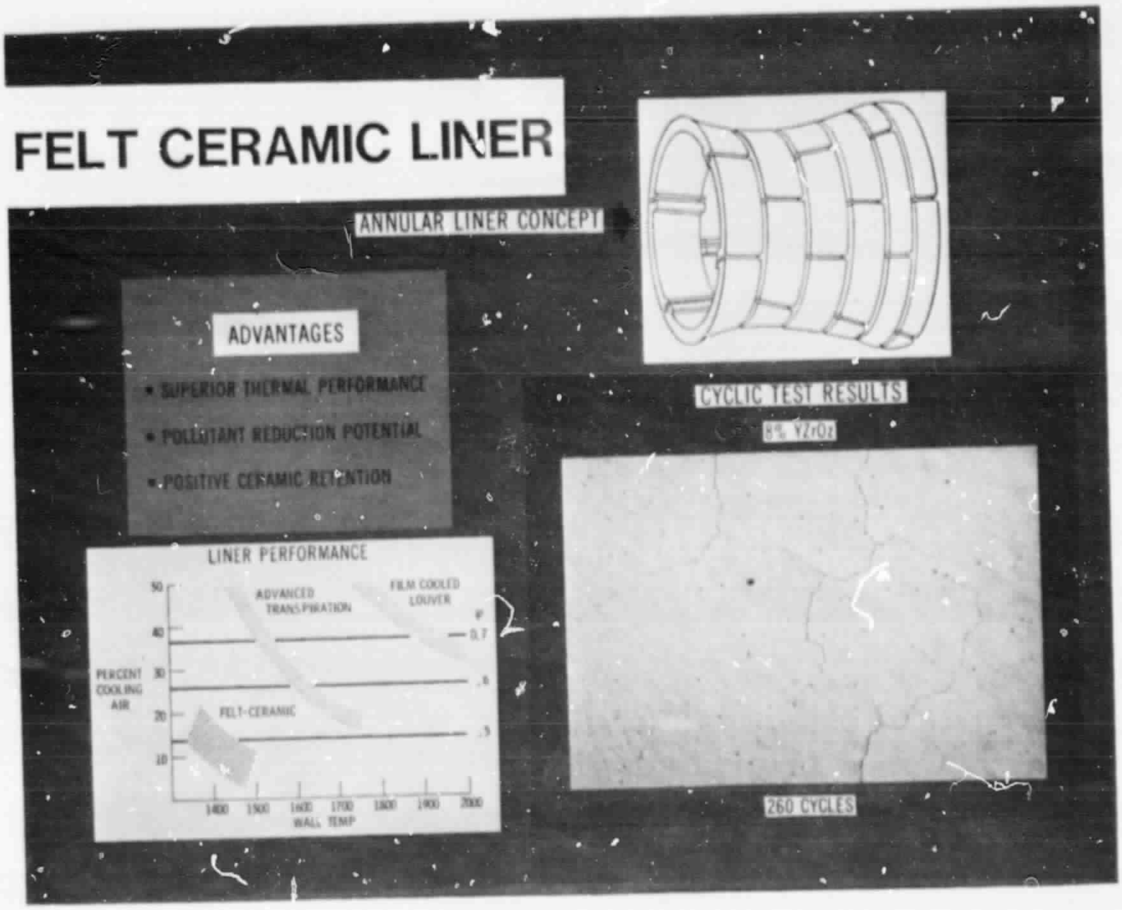

FIGURE 12

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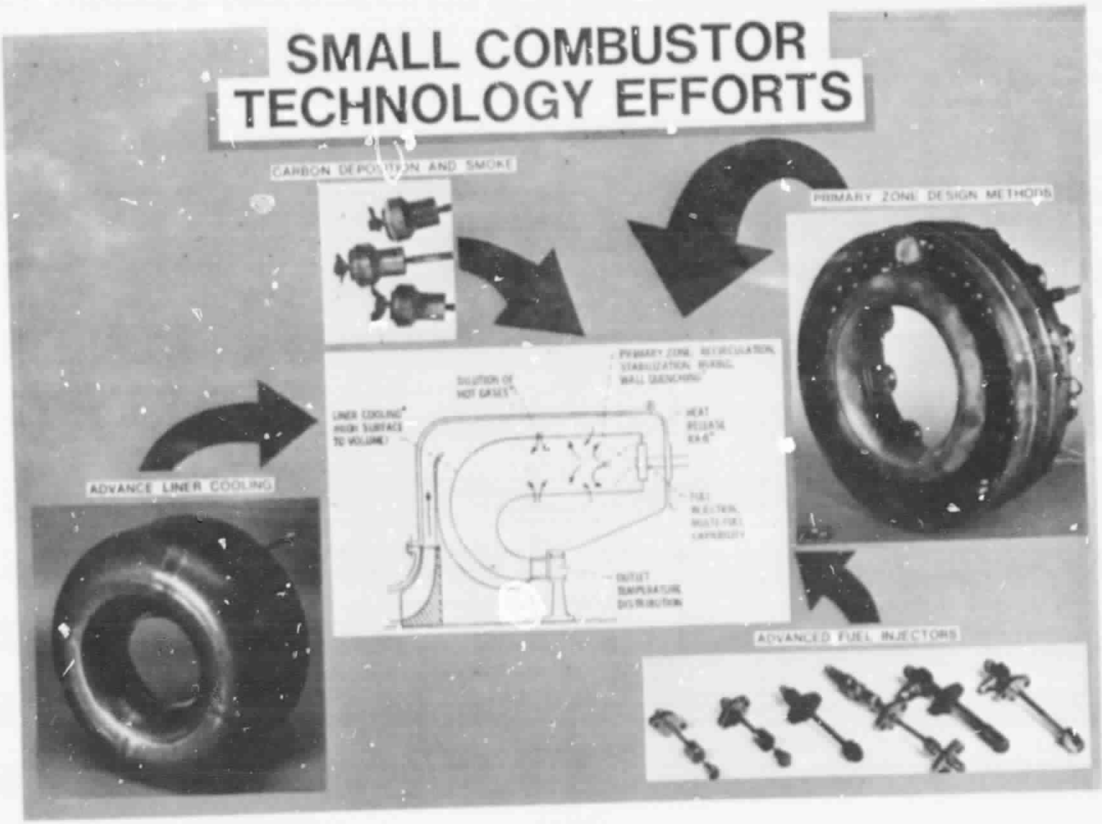

FIGURE 13

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TURBINE PERFORMANCE COMPARISONS

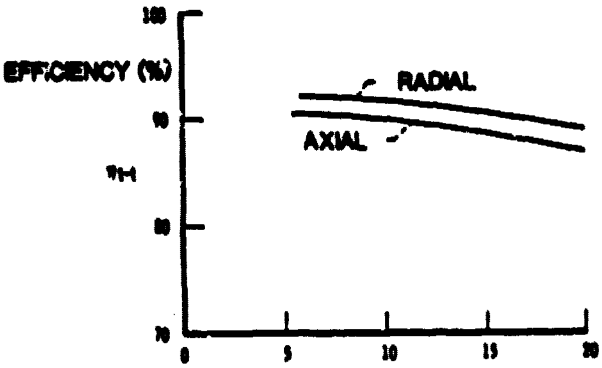

FIGURE 14

VARIABLE AREA RADIAL TURBINE

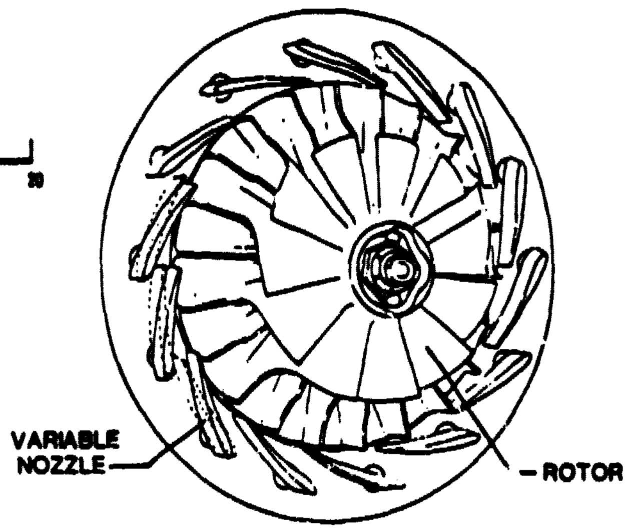

FIGURE 15

VARIABLE GEOMETRY RADIAL TURBINE

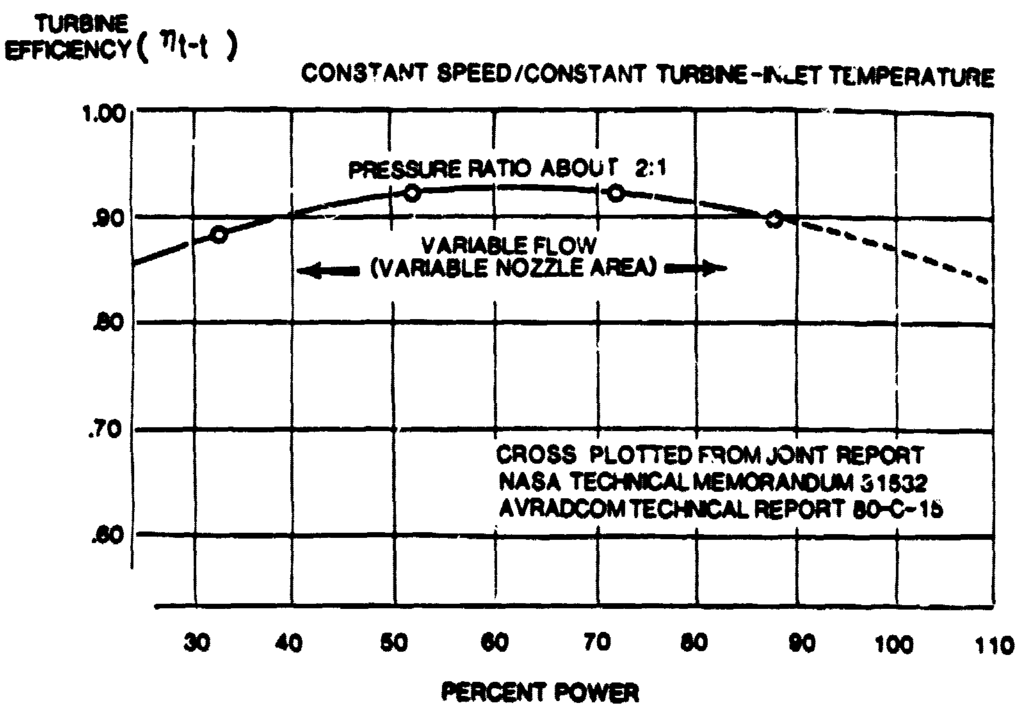

FIGURE 16

SPIRAL-GROOVE SEAL

FIGURE 17

TURBINE TIP CLEARANCE LOSSES

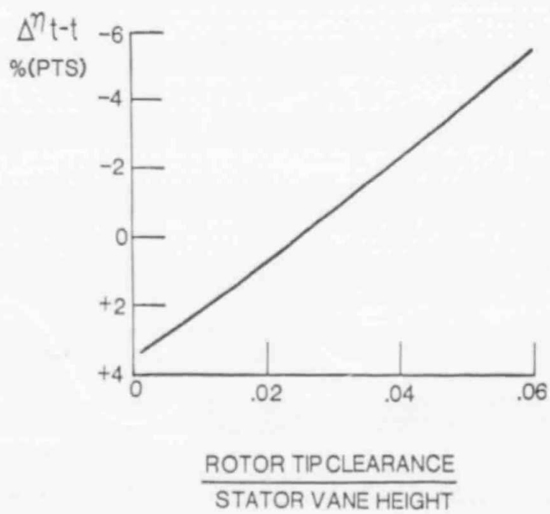

FIGURE 18

TURBINE SHROUD

STRAIN-ISOLATOR PAD CONCEPT

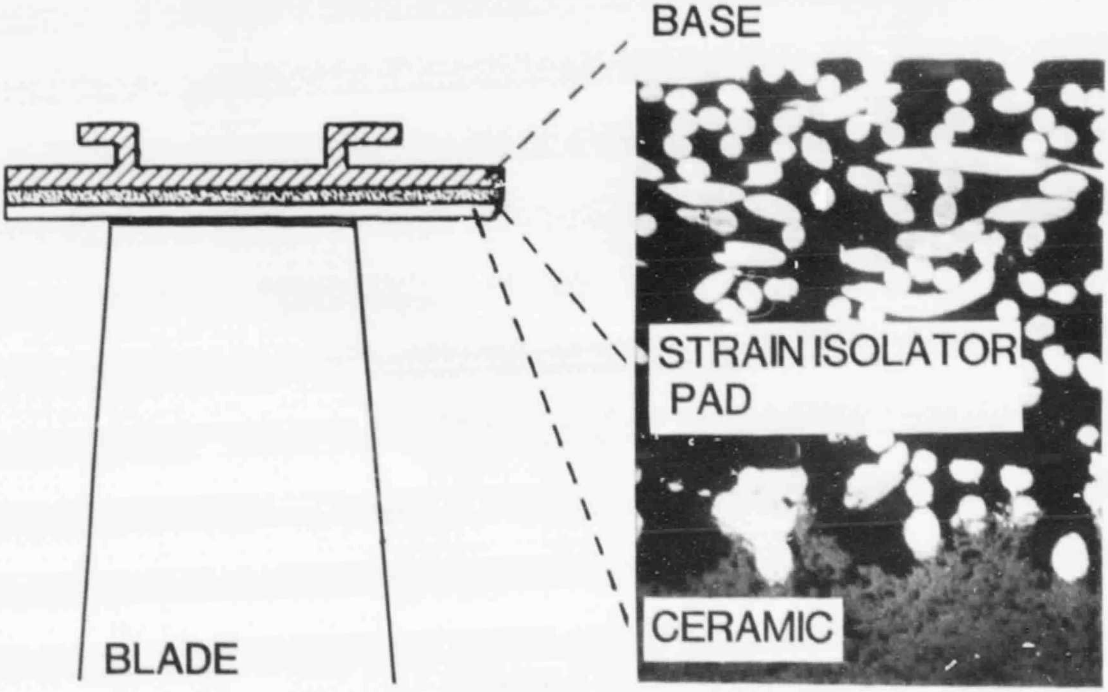

FIGURE 19

CS-81-2266